

Surveying the dark side

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We examine the prospects for the next generation of surveys aimed at elucidating the nature of dark energy. We review the methods that can be used to determine the redshift evolution of the dark energy equation of state parameter w , highlighting their respective strengths and potential weaknesses. All of the attractive methods require surveys covering more than 5–10,000 sq. deg. of the sky. We examine the accuracy that each method is likely to deliver within a decade, and discuss the difficulties arising from systematic uncertainties associated with the techniques.

We conclude that the proposed photometric and redshift surveys have the potential of delivering measurements of w with percent accuracy at several redshifts out to $z \sim 3$. Of particular interest will be the combination of weak lensing and baryonic acoustic oscillations measurements. This exquisite precision is likely to have a fundamental impact on our understanding of the nature of dark energy, providing the necessary guidance for its theoretical explanation.

1. THE DARK SECTOR OF THE UNIVERSE

One of the most fundamental problems of contemporary physics is to elucidate the nature of the “Dark Sector” of the Universe. A wealth of cosmological observations seem presently to point to a concordance cosmological model based on the Big Bang theory and an homogeneous and isotropic Universe. Observations ranging from measurements of temperature anisotropies in the cosmic microwave background (CMB) to data on the abundance of hydrogen and other light elements in the Universe indicate that “normal” (i.e. baryonic) matter accounts for a mere 4% of the matter–energy contents of the cosmos. The remaining 96% makes up the so-called “Dark Sector”, with about 19% of cold dark matter (CDM) and 77% of “dark energy”. The details of this cosmic budget vary somewhat depending on the data sets used and the assumptions one makes, but the errors on the different components are below 10% (see eg [1, 2] for details).

Direct evidence for the presence of non-baryonic, massive, cold dark matter comes from observations of its gravitational effect on eg the rotation curves of galaxies, or on the propagation of light from distant sources (gravitational lensing). Further evidence comes from the CMB, through which we now measure the epoch of matter–radiation equality with better than 10% accuracy. From the theoretical point of view, there are many well-motivated candidates for dark matter, for instance coming from supersymmetric theories beyond the standard model of particle physics. Direct and indirect detection experiments are now starting to probe interesting regions of parameter space, and the direct discovery

of dark matter might well be within reach (see [3] for an example).

The situation is different as far as dark energy is concerned. Observations of distant supernovae type Ia show that their apparent luminosity is less than what one would expect in a matter-dominated Universe [4, 5, 6]. This has been interpreted as evidence for an accelerated expansion, that could be caused by a new form of energy with negative pressure, dubbed “dark energy”, whose energy density is about three times that of matter at the present cosmic time [7, 8]. Similar conclusions can be reached by combining the CMB data with observations of galaxy clustering (see eg [2]). An alternative explanation might lie in a change in our theory of gravity, for instance by modifying General Relativity on cosmological scales [9, 10, 11]. Distinguishing between these two scenarios (ie, dark energy as a modification to the equations of General Relativity or as the manifestation of a new exotic source) is one of the main goals of upcoming investigations.

2. THE NATURE OF DARK ENERGY

The difficulty comes from the fact that there is presently no compelling theoretical explanation for the existence of dark energy, nor for its present energy density. Guidance as to the nature of dark energy has therefore to come from new observational evidence. Only a better grasp on the properties of dark energy will allow to solve outstanding questions such as the “coincidence problem”, i.e. why is the proportion of dark energy to dark matter of order 1 just now in cosmic history? Did this happen simply by chance, or perhaps in virtue of some anthropic principle, or because of some more fundamental, yet unknown reason? There is also a “fine tuning” problem, linked with the small magnitude of the

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dark energy density, which lies at least 60 orders of magnitude below theoretical expectations coming from particle physics. From this point of view, the central question is why is the energy scale of dark energy so small with respect to other known scales of fundamental physics (the Planck scale or the supersymmetry breaking scale)?

Advancements on all of those topics require stronger observational proof of the properties of dark energy today and in the past. A first important step is to discriminate between an evolving dark energy (whose energy density changes with cosmic time) and a cosmological constant of the form proposed by Einstein in the 1910s. A handle on this question is offered by the equation of state parameter, w , that measures the ratio of pressure to energy density of dark energy. If one could determine with high accuracy that $w = -1$ and constant in time, this would strongly support the case for a cosmological constant. This would imply that dark energy is a manifestation of a new constant of Nature, whose magnitude would however suffer from the above fine tuning problem. Detecting an evolution with redshift of $w(z)$ would support a dynamical form of dark energy, perhaps in the form of a scalar field that could be linked to the inflationary phase of the early Universe. Either one of these results is likely to have a major impact on our knowledge of fundamental physics.

Current data are consistent with $w = -1$ out to a redshift of about 1. The uncertainty depends very much on the data sets used and on the assumptions about the underlying model. If one models dark energy in terms of w_{eff} , an effective equation of state that is constant but might be different from -1 (that can be understood in terms of appropriate weighting functions depending on the observable, see [12]), then the uncertainty is of order 5 – 10%, by using all of the available data sets (CMB, SNe, Lyman-alpha absorption systems and large-scale structure) [13, 14, 15]. However, one must be very careful when assessing the combined constraining power of different data sets whenever each one of them does not provide strong constraints when taken alone. Combination of mutually inconsistent data can potentially lead to unwarranted conclusions on the dark energy parameters. This is why it is very important to develop techniques that can determine w accurately without the need of combining many different measurements together.

A number of techniques can be used to investigate the nature of dark energy, and they are reviewed in the next section.

3. PROBES OF DARK ENERGY

The observable impact of dark energy can be broadly divided in two classes: modification of the redshift–distance relation and effects on the growth of structures. Accordingly, we can divide the different methods outlined below following the effect through which they are mainly sensitive to dark energy: *probes of the redshift–distance*

relation (supernovae as standard candles, acoustic oscillations as standard rulers) and *probes of the growth of structures* (galaxy clustering, number counts, weak lensing, Integrated Sachs–Wolfe effect).

We briefly describe each one in turn, highlighting their respective advantages and weaknesses. Methods are listed in order of approximately increasing number of assumptions about the physical processes under observation, from the most “clean” (ISW, weak lensing and baryonic acoustic oscillations) to the ones which require the most assumptions and are therefore less suited to robustly probe dark energy.

The Integrated Sachs–Wolfe effect. The transition from a matter dominated to the dark energy dominated epoch induces a time variation of the gravitational potentials, which in turn changes the temperature of cosmic microwave background photons as they traverse matter overdensities [16]. This is called (late) integrated Sachs–Wolfe effect (ISW), and its measurement requires the correlation of high-quality CMB maps with a large survey of the galaxy distribution covering many thousands of square degrees, under the assumption that light traces matter.

The ISW effect is a direct probe of the existence of dark energy, but currently the significance of its detection is still low [17, 18]. The cross-correlation measures the product of the growth function of density perturbations and its time derivative averaged over a range of redshifts, which is in principle a sensitive tracer of the dark energy equation of state. However, the statistical power of the method is limited by the fact that the signal is present only on large scales and at low redshifts, where cosmic variance (the fact that we have only one realization of the Universe to observe) hinders the accuracy of the test [19, 20]. The ISW effect is thus not competitive with the statistical precision of the other methods to determine a possible time–evolution of dark energy.

Weak gravitational lensing. The distribution of matter in the Universe causes gravitational bending of the light coming from distant sources. The distortion pattern induced in the shape of background galaxies and the change in their surface density (magnification) by the intervening matter distribution can be studied statistically. The measured signal is sensitive to a combination of the geometry of the Universe, the growth and distribution of structures, and the position of the sources (see eg [21] and references therein).

Information about the redshift distribution of the sources can be exploited at different levels. Until now, the first generation surveys have essentially measured 2–dimensional projections of the lensing signal along the line-of-sight [22, 23]. The next generation surveys will use photometric redshifts of the lensed galaxies to perform an analysis in several redshift bins (“cosmic tomography” [24]) to invert the lensing equations to deduce the 3–dimensional gravitational potential (“3D reconstruction” [25, 26]) or to carry out a geometric test for dark energy [27]. Even a relatively coarse division in 3 bins

out to a redshift of $z = 1$ can improve constraints on the dark energy equation of state by a factor of 5 to 10 with respect to the 2D analysis.

The fundamental physics of weak lensing is well-known and the method has the key advantage that it does not need to make any assumption whatsoever about the mass-to-light relation. It is therefore a very “clean” technique. This is potentially the single most accurate method to study dark energy, but in order to achieve the exquisite statistical accuracy it promises, a series of systematic errors must be carefully controlled. Low seeing (below 0.9 arcsec) is essential in order that accurate shapes can be measured for sufficient numbers of distant background galaxies. Since the weak lensing shear pattern presents distortions in the shape of galaxies at the level of 1% (0.1%) on arcminute (degree) scale, an accurate correction for instrument distortion is required in order to extract the low amplitude cosmological signal. The uncertainties in the photo- z calibration must be controlled with exquisite accuracy (well below 1% in random errors and systematic bias), lest the tomographic advantage is destroyed [28]. This is challenging but not unfeasible and it requires large (of order of 10^4) spectroscopic training sets. An important contamination is intrinsic alignments between galaxies, which can be mistaken for a cosmic shear signal. Fortunately, photo- z information on the sources can be used to down-weight pairs of galaxies which lie close in redshift, thereby completely removing the intrinsic alignment of the sources. Furthermore, the decomposition of the shear signal in curl and gradient modes (called B and E modes, respectively) allows for an important check of unsubtracted systematics, since the weak lensing image distortions are curl-free to first order [29]. There is however another subtle effect (gravitational-intrinsic correlations) which survives this procedure, and which could potentially contaminate the signal at the level of 10%, without showing up in the B modes. Correlation across different redshift bins could be used to decontaminate the signal from this effect but this is a poorly understood systematic effect and research is currently ongoing [30]. Mixing of the E and B modes due to lack of shear correlation measurements is also a potential source of systematic error [31].

Large-scale structures and acoustic oscillations.

From a galaxy catalogue it is possible to extract the matter power spectrum, given a model for the mass-to-light relation (bias). The shape of the matter power spectrum probes mainly the matter to radiation content and the spectral tilt of the primordial fluctuations. When combined with CMB and/or SNe data, this yields an indirect indication of the presence of dark energy, by selecting a Universe with low mass density (see eg [32]).

However, another approach based on a measure of standard rulers is possible, since the tight coupling regime prior to recombination imprints a characteristic oscillation scale in the power spectrum. In the early Universe, gravitational compression of matter overdensities is counterbalanced by radiation pressure in the photon-

baryon plasma. This results in acoustic waves that are frozen ar recombination. Their characteristic scale, given by the length sound could travel before recombination, has been imprinted on the cosmic microwave background in the form of the oscillatory peaks we now observe in the CMB power spectrum. This process also leads to a preferred scale in the matter distribution, corresponding to the acoustic horizon scale. “Acoustic oscillations” or “baryon wiggles” appear in the correlation function of galaxies as a bump that can be used as a standard ruler for cosmological distance measurements [33, 34, 35]. The effect has been recently detected in the correlation function of Luminous Red Galaxies of the SDSS [36] as well as in the 2dF Galxy Redshift catalogue [37].

At a given redshift, a measurement of the acoustic scale in the direction transverse to the line of sight gives the angular diameter distance, while the radial direction delivers a direct measurement of the evolution of the Hubble parameter. Extracting information on dark energy evolution requires two derivatives of the former, but only one of the latter quantity. If the length scale of the acoustic oscillations is known (eg, by calibrating it against the observed peaks in the CMB angular power spectrum), then the angular diameter distance and the Hubble rate are measured absolutely by the above method. If such an absolute calibration is not available, they are measured in units of the present Hubble parameter, in which case the method needs to be calibrated against a local measurement of the expansion rate. The Alcock-Paczynski test is a weaker version of this procedure, in that it does not determine the angular diameter distance and the Hubble expansion separately, but only their product, by comparing the extension of the standard ruler in the transverse and radial directions at a given redshift.

To exploit fully the potential of acoustic oscillations, spectroscopic redshifts are necessary to resolve the radial direction, since photometric redshift information is not accurate enough to measure the ruler in the redshift dimension. The washing out of the radial direction means that a photometric survey must cover about 20 times a larger area than a spectroscopic one to achieve the same sensitivity to dark energy with the acoustic oscillations technique [38]. This method requires at the same time deep and wide surveys and is therefore very expensive in terms of observing time. The advantage of the technique is that the observation of the acoustic signature is very robust to systematic errors, and non-linear effects, galaxy biasing, redshift and lensing distortions can be corrected for with good confidence [39, 40], even though further work is required to refine our understanding of galaxy formation and evolution ([41], but see also [42]). Furthermore, since the Hubble rate is the derivative of the angular diameter distance, measuring both at the same time provides an internal consistency cross-check. Another key advantage is that measuring both quantities breaks a strong degeneracy between the equation of state of dark energy and the curvature of the Universe, allowing to distinguish between the two.

Supernovae type Ia. If the intrinsic luminosity of an object and its redshift are known, measuring the flux at the observer’s position allows to reconstruct the luminosity distance to it. The luminosity distance is an integral over redshift which depends on the matter–energy content of the Universe. The presence of dark energy in the form of a cosmological constant, for instance, makes distant objects appear fainter by accelerating the expansion of the Universe.

Light curves of stellar explosions known as supernovae type Ia (SNe) can be empirically calibrated to give such a “standard candle”, and provided the first evidence of an accelerated expansion and of the existence of dark energy in the late ’90s [5, 6], that has been recently confirmed by observations of supernovae at $z > 1$ [4, 43]. This method only measures ratio of distances out to $z < 1.5$ (see also [44] for a discussion). It is therefore important that distant supernovae can be empirically re-calibrated on local ones. The danger with SNe methods is that the progenitors, and thus the correction, may evolve systematically with redshift. This potential systematic problem requires careful control through spectroscopy. Future SN surveys will need to achieve better than 1% control on SNe evolution. Large surveys detecting thousands of SNe will allow a better control of this systematic by only selecting similar galaxies at different redshifts. However, it will be difficult to follow-up each SN spectroscopically, and therefore it becomes important to be able to correctly select SNe type Ia directly from the imaging survey, and to collect enough information on their light curve to allow their recalibration. The main systematics floor for this methods comes from our imperfect knowledge of the details driving supernova Ia explosions.

Clusters number counts. The value of the cosmological parameters and dark energy properties can be constrained through the cluster redshift distribution, which measures the number of clusters per comoving volume per solid angle above a certain mass threshold. The cluster mass can be estimated for instance through the Sunyaev–Zel’dovich (SZ) effect, an increase in the temperature of CMB photons produced by the rescattering of such photons by the hot clusters gas they traverse. An alternative method of selecting clusters would be using the galaxy colours, e.g. the red sequence technique [45]. The approach of combining this selection method with self-calibration may perform as well as SZ-selection with the advantage that the clusters can be selected directly from the imaging catalogue. The sensitivity to dark energy comes in via the Hubble parameter, the angular diameter distance and the mass selection function.

Unknown aspects of cluster physics might be an hindrance to applications of this method for cosmology, and in particular for dark energy studies. Of the methods proposed, this is arguably the most susceptible to systematic errors induced by our imperfect knowledge of cluster physics. The problem is that the abundance of clusters is exponentially dependent on mass, and therefore a small error in mass implies a large mistake in abundance. Thus,

although changes in the equation of state of dark energy result in large variations at a given mass, the conversion between observable quantities and cluster mass is highly uncertain (in both random and systematic senses).

The success of the method will rely on “self-calibration” techniques that use the clustering of the clusters and the weak lensing shear pattern around the cluster as additional constraints [46]. The ultimate precision that can be achieved with these correction methods is not yet clear, and this is an area of very active research.

4. THE NEXT GENERATION OF SURVEYS

Ambitious observational campaigns targeting a combination of the above techniques are being planned and will be carried out with a new generation of instruments in the next decade. The field is moving extremely fast, and funding agencies all over the world (including PPARC, NASA, the US Department of Energy and ESO) have given dark energy studies a considerable strategic priority. The goals are on one hand to reduce the error on the dark energy equation of state to the 1% level, and on the other hand to explore alternative explanations to the accelerated expansion. Both of them will require a combination of the techniques outlined above, but weak lensing and acoustic oscillations together appear to be the most promising ones, both in terms of accuracy and for maximising the discovery space.

4.1. Imaging surveys

Proposals for the next generation of imaging surveys driven by dark energy science typically feature a survey area covering 5,000 to 10,000 square degrees, a large field of view (2 square degrees or more) and four to five optical photometric bands. Those are the basic specifications for both the *Dark Energy Survey* (DES, see [47]) and *darkCAM*, which would have optical cameras mounted on 4m class telescopes. DES is a US-led collaboration that will use a 520 megapixel CCD camera mounted on the Blanco telescope to image 300 million galaxies at a median redshift of $z \sim 0.7$ and to carry out weak lensing, baryonic oscillations, cluster counts and SNe observations over 5 years, starting in 2009. The UK involvement is led by UCL and has recently been backed up by PPARC. The European UK-led *darkCAM* proposal to image some 10^9 galaxies with weak lensing image quality was originally envisaged to share time on ESO’s VISTA, but is now looking at a full-time site.

One of the most advanced projects is the *Pan-STARRS* survey (Panoramic Survey Telescope and Rapid Response System, [48]), a US Air Force funded project in Hawaii, primarily devoted to the identification of Earth-approaching objects, but with 30% of its time dedicated to supernovae, baryon oscillations and weak lensing surveys. The first of the planned four 1.8m telescopes is

currently undergoing commissioning, and the full system could be online by about 2009, representing a major increase in power with respect to present-day surveys.

In purely statistical terms, the most precise constraints on the dark energy equation of state are likely to come from weak lensing. The details depend very much on which assumptions are made about the cosmology and on which other data sets are included. Another important factor is whether the analysis is restricted to the safe linear regime or whether it includes smaller scales modes, which give more aggressive constraints but might suffer from less well controlled non-linear effects. On the bright side, correlations among different observables can be constructed from the survey, which will help improving both the statistical accuracy by breaking parameter degeneracies and the control on systematics: the correlation between foreground galaxies number density (galaxy–galaxy correlation) and between foreground galaxies and shear pattern (galaxy–shear cross-correlation). Using all of this information, weak lensing alone could achieve better than 5% accuracy on the effective equation of state, while in combination with CMB anisotropies measurements of Planck quality (an ESA satellite mission due for launch at the beginning of 2008 [49]) an accuracy of 1–2% might be within reach.

This is of course only achievable if all of the systematic errors will be kept closely under control. This means an exquisite image quality, good seeing conditions (below 0.9 arcsec), excellent photometric redshift reconstruction and control of intrinsic and gravitational–intrinsic correlations. Arguably, the major hindrance in pushing weak lensing constraints below the 5% mark will indeed come from systematic error control.

The clusters and SNe method will be considerably less stringent, roughly a factor of 3 to 4 less precise than weak lensing, unless combined with strong CMB priors (i.e., Planck data), in which case they will perform at about the 5% level. The performance of the cluster count technique relies however on self-calibration using clustering and weak lensing data, a difficult procedure compounded by the challenge of controlling systematic errors at this level of precision. The possibility of SNe evolution and missing pieces in our understanding of how a supernova explosion comes about are also likely to be limiting factors when trying to increase the accuracy on the equation of state below the 10–5% limit with this technique. Finally, measurements of acoustic oscillations from imaging surveys are not competitive with the other methods in terms of precision, reaching down to only about 20% accuracy because of the lack of resolving power in the radial direction (but see also [50]).

While none of the methods described above possess by itself all of the *desiderata* that we would ideally want in trying to constrain dark energy, combination of (at least) two techniques offers many advantages. It allows for cross-calibration of observables and facilitates cross-checks of systematics, since the physical underpinnings of each observable are different, and so is the nature of

the possible systematic errors. This last aspect is very important in order to test the idea that dark energy is indeed a new source in Einstein’s equations (rather than e.g. the manifestation of a different theory of gravity): by comparing observables which are mainly sensitive to the growth of structures with tests of the redshift–distance relation, we can look for inconsistencies that cannot be explained by dark energy in the form of a new fluid.

In view of this, a very promising combination is given by weak lensing and baryonic acoustic oscillations, which together offer the advantages of potentially high accuracy (weak lensing) and robustness to systematics (acoustic oscillations). They independently probe the growth of structures (lensing) and the angular diameter distance relation (acoustic oscillations, once calibrated against the high-redshift ruler given by the CMB). As mentioned above, spectrographic redshift surveys encompassing millions of galaxies will be needed to exploit fully the potential of acoustic oscillations. We now turn to discuss the observational perspectives in this field.

4.2. Spectrographic surveys

There are a number of redshift surveys at various stages of planning, development or commissioning, that will have among their main science drivers measurements of the acoustic ruler at different redshifts.

Perhaps the most ambitious is the *Wide-Field Multi-Object Spectrograph (WF MOS)* [51], a proposal for a 1.5 deg² multi-object spectrograph which will be able to observe 4,000 to 5,000 objects simultaneously. The instrument is to be developed collaboratively by the Gemini and Subaru Observatories and will be deployed on the 8m Subaru telescope on Mauna Kea, Hawaii. Two baseline surveys are being proposed: a shallower and wider one, covering 2,000 square degrees at $z \sim 1$ which will target emission line blue galaxies; and a deeper one, over 300 square degrees at $z \sim 3$ targeting Lyman-Break Galaxies. The timescale for the deployment is 2013, with results over the first 500 square degrees due by the end of 2013 and completion of the survey anticipated for 2016. Conceptual design studies are currently being carried out.

The two WF MOS proposed baseline surveys will determine the angular diameter distance and the Hubble expansion rate at $z \sim 1$ and $z \sim 3$ with 1–2% accuracy. The corresponding constraints on the dark energy equation of state rely on the calibration of the acoustic scale to Planck-like CMB observations and on an independent measure of either the Hubble parameter or the dark matter density parameter (eg via the matter power spectrum). Combination with Planck forecasts and SDSS data gives an accuracy in the range of 5–10% in the effective equation of state. If one drops the assumption of flatness, a constant w_{eff} can be constrained to 5% precision by combining WF MOS acoustic oscillations measurements with SNe data, thus breaking an important degeneracy between dark energy and spatial curvature.

On a shorter timescale, there are proposals to use the *AAOmega* wide-field spectrograph – an upgrade to the 2dF spectrograph for the Anglo-Australian Telescope, which has now been successfully commissioned – to carry out large surveys (between 500 and 1,000 deg^2) in the redshift range $0.3 < z < 1$ to achieve 2% accuracy in the angular diameter distance and the expansion rate.

A rather more revolutionary concept is being investigated for the *VIRUS* spectrograph, a proposal for the 9m Hobby-Eberly Telescope in Texas based on industrial replication of low-cost components [52]. The aim is to measure $5 \cdot 10^5$ galaxies in a deep ($1.8 < z < 3.7$) and narrow (200 deg^2) survey by 2010, aiming to an accuracy of 1–2% in the diameter distance and the expansion rate. *VIRUS* is based on a panoramic integral field spectrograph operated blindly without target pre-selection and the technical feasibility of the survey is being tested with a pilot project encompassing 10% of the modules.

In summary, the statistical accuracy from acoustic oscillations redshift surveys is less than what could be achieved with weak lensing. However, the acoustic oscillation method seems to be much more robust with respect to systematic errors, and it can probe a deeper redshift range than any other method. While a single measurement of the acoustic scale at intermediate redshifts ($z < 1$) compared with the scale set by the CMB ($z \sim 1100$) gives the largest lever arm for constraining dark energy, it would be very interesting to measure the acoustic scale also in the deep region, $z \sim 3$. This would allow to isolate unexpected physical phenomena in the as yet unexplored range $3 < z < 1100$ (e.g. extra relativistic degrees of freedom), to observe the deceleration epoch when dark energy is supposedly sub-dominant and therefore check for an exotic dynamical behavior at $z > 1$. A deep measurement would also help in constraining deviations from Einstein gravity that would not appear in tests based on the growth of structures (see [53] for an illustration).

The WFMOS survey will require pre-selection of targets in the desired redshift range, which should not represent a major obstacle in the shallow region ($z \sim 1$), given that many spectroscopic surveys (CFHT, Pan-STARRS, DES, VST-KIDS) should provide the necessary coverage by 2012. The selection at high redshift ($z \sim 3$) will require further effort to complement the existing imaging data. A possible strategy is represented by Hyper-Suprime, a proposal for a wide-field, 3 deg^2 camera for the Subaru Telescope. This instrument would be able to produce a high-quality weak lensing survey in 4 or 5 colours over 2,000 deg^2 , which would be especially useful in conjunction with WFMOS, covering the same region of the sky. Together, Hyper-Suprime and WFMOS could exploit the complementarity between weak lensing and acoustic oscillations, and WFMOS spectroscopy would provide the necessary training sets for the weak lensing tomography. Construction of Hyper-Suprime could optimistically begin in 2009–2010, but the project is currently only in the preliminary design phase and the funding sta-

tus is uncertain.

4.3. Synergies between surveys and methods

Dark energy science is a field that can benefit enormously by the convergence of different observations, for the reasons recalled above. In particular, the synergy with the next generation of CMB experiment will be very important, either because this offers a high-redshift calibration standard for acoustic rulers, or because CMB data help reducing or breaking degeneracies between dark energy and cosmological parameters.

Conversely, measurements of primordial B-modes (induced by gravitational waves) in the CMB can profit from weak lensing observations, by using them to subtract the contaminant signal coming from line-of-sight lensing. For weak lensing, the availability of IR photometric bands (for instance from the VISTA IR survey) to complement visible photometry would yield considerable improvement in the redshift accuracy for sources beyond $z \sim 1$, thereby helping in performing weak lensing tomography.

Regarding acoustic oscillations, the most important limitation to the absolute calibration is the accuracy with which the total matter density is known. The present-day accuracy of 10% is insufficient for WFMOS, but it is expected that Planck will improve this by a factor of 10, which would be enough to make this uncertainty subdominant. For evolving models of dark energy and/or a non-flat Universe, a precise knowledge of local standards (i.e. the present Hubble parameter or matter density parameter) would help to considerably tighten constraints. This can be achieved with a variety of methods (SNe observations, shape of the matter power spectrum, weak lensing, distance ladder measurements of the Hubble parameter). The most useful single measurement is probably SNe, since the degeneracy lines are oriented differently in parameter space, and this would assist in breaking a degeneracy between dark energy and spatial curvature.

Cluster selection and mass determination will be pursued by DES by matching the area covered by the South Pole Telescope, a CMB mission that is expected to measure some 20,000 clusters via the SZ effect by 2009 [54], another interesting example of combination of techniques.

4.4. A look into the future

There is a series of proposals for next-to-next generation of instruments, which aim at taking dark energy investigations to an even more ambitious level.

The *LSST* (Large Synoptic Survey Telescope) is a project for a wide-field, 8.4m telescope and a 3 Gpixels camera [55, 56]. The survey will cover the whole of the Southern hemisphere (or 20,000 deg^2) multiple times per month with 6 colours photometry. It will survey

the largest volume ever proved, extending in the range $0.5 < z < 3$, and it will use a variety of techniques (weak lensing, acoustic oscillations, cluster abundance and a staggering 250,000 SNe per year) to constrain dark energy at the percent level. The enormous volume means that LSST is a potential competitor to spectroscopic surveys such as WFMOS, as well, since the volume of LSST compensates for the fact that its photometric redshifts will not be able to resolve the radial mode in the acoustic oscillations. However, this assumes that it will be possible to obtain precise high-redshift photometric information without the use of spectroscopic training sets, the prospects of which are uncertain. The project is moving quickly and a very recent development saw the award of substantial funding by the National Science Foundation to carry on with the design and development stage. The current schedule expects construction to begin in 2009 and first light in 2013. Science will start in 2014. The enterprise is technologically very challenging and a great amount of research and development is still required to meet the specifications for the telescope, the camera and the data analysis pipeline. Once online, the LSST will quickly overtake all other surveys thanks to its vastly superior survey speed.

The second half of the next decade will also see a great leap forward in radio astronomy, as the SKA (Square Kilometer Array) begins operations, first as a pathfinder (around 2015) and then as a full system with a total collecting area of a million square meters (around 2020) [57]. Thanks to its huge field of view, the SKA will be able to measure redshifts of a billion of galaxy over half of the sky in only a few months of operations, by detecting radio emissions from hydrogen gas (see eg [58]). The project is now beginning the design study phase, thanks to a recent funding decision by the European partners, including PPARC.

The possibility of a dark energy space mission remains uncertain at the moment, with NASA and the US Department of Energy reconsidering their strategic priorities regarding the concept of a Joint Dark Energy Mission (JDEM), which is however unlikely to be realized before the second half of the next decade.

5. SUMMARY

Among all of the techniques reviewed, the most promising for dark energy are weak lensing and acoustic oscillations, because of their statistical accuracy (weak lensing) and robustness to systematic errors (acoustic oscillations).

The weak lensing technique assumes only General Relativity and the cosmological principle and it is based on well-known physics (gravitational bending of light). The lensing signal is a combination of the growth of structures, the cosmology and the distribution of sources. Photometric redshifts are used to reconstruct the radial dependence of the signal. Weak lensing measurements

can constrain the equation of state of dark energy out to a redshift $z \sim 1$ to 1–2% accuracy given a 5,000 to 10,000 square degrees, high-quality imaging survey in four to five colour bands, with mild assumptions about the cosmology (eg priors from CMB experiments). This represents a 5 to 10-fold improvement over present-day constraints in this redshift range. Achieving this precision requires an exquisite control of various systematic errors, the dominant ones being photo- z accuracy, image quality and intrinsic and galaxy-intrinsic correlations. This calls for a factor of 10 improvement over current techniques – a difficult but not unfeasible task. There are several in-built techniques which can be used to cross-check for internal consistency and systematics.

Observations of baryonic oscillations with a spectroscopic survey have less statistical power than weak lensing (roughly a factor of 5), but are less prone to systematic errors due to the characteristics of the acoustic signature. The phenomenon of acoustic oscillations is based on linear physics (at least at high enough redshifts) that is well known from the CMB. The oscillations' scale is used as a standard ruler to determine the cosmology and is largely independent of the growth of structures. The ruler needs to be absolutely calibrated to high-redshifts standards (the CMB) and to local standards (the Hubble parameter or matter density parameter). The method gives a complementary and independent measurement of dark energy at intermediate, $z \sim 1$ redshift. It is also the only technique which can probe the high-redshift evolution at $z \sim 3$, and check for consistency in the dark energy evolution as inferred from lower-redshifts probes.

It is also important to keep in mind that upcoming imaging surveys such as DES, darkCAM or Pan-STARRS will produce a vast amount of results in other fields apart from dark energy science, eg galaxy and galaxy clustering evolution, star formation studies, high-redshift quasars detection and evolution, local galaxy studies, strong lensing, microlensing, near-earth objects and outer solar system investigations, radio AGN's.

The WFMOS instrument will use spectroscopic redshifts of millions of galaxies to detect the acoustic signature in the intermediate and deep redshift range. When properly calibrated, this will allow to reconstruct the redshift-distance relation and the expansion rate with 1–2% accuracy out to recombination time. With early results expected for 2013–2014, WFMOS has the potential of pioneering the field of wide and deep spectroscopic reconstruction of the acoustic oscillations. Intermediate steps towards this goals might be taken by the AAOmega spectrograph on a shorter timescale.

In conclusion, the observational study of dark energy is a crucial area of cosmological research. This is one of the most challenging problems in contemporary physics, the solution of which is likely to spark a new understanding of fundamental physics. Thanks to a host of ambitious proposals and a strong support by several funding bodies, key advances are likely to be made within the next decade.

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